

JPL Report
DRS CL 96-1349

Electromigration Analysis for Cassini Microcircuits



Cassini Spacecraft

November 20, 1996

NASA
National Aeronautics and
Space Administration

JPL
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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TABLE OF CONTENTS

| | | |
|---------|-----|---|
| Section | 1.0 | Introduction |
| Section | 2.0 | Results |
| Section | 3.0 | Approach |
| Section | 4.0 | Analysis Details |
| Section | 5.0 | Results |
| Section | 6.0 | Stress Voids and Electromigration Concern |
| Section | 7.0 | Summary |
| Section | 8.0 | Recommendations |

Attachments:

- (1) December 6, 1995, Subject: Conclusions from Harris Metal Stress Voids Concerns, Meeting July 21, 1995
- (2) Example of Cassini Electromigration Data Base Calculations
- (3) Example of Detail Report Used by SRE & Part Specialist

Section 1.0

Introduction

An electromigration probability analysis was performed for devices susceptible to electromigration. The devices analyzed were the electronic parts supplied for Destructive Physical Analysis (DPA) with each lot of microcircuits and transistors received. This covers the vast majority of electronic parts used on the Cassini spacecraft. There were a few exceptions where other arrangements were made for those devices not covered here, but were covered as defined in the particular contracts involved.

The electromigration analysis is needed because the military specification Mil-M-38510 current density limitation of 5×10^5 Amps /cm² cross-section does not guarantee a part will meet its lifetime requirement for a long mission such as Cassini. The current density is only part of the Mean-Time-To-Failure (MTTF) electromigration equation. A more complete analysis is required that takes into account the other factors of the electromigration MTTF and probability equations.

Section 2.0 Results

All microcircuits and transistors analyzed passed the established criteria, except in one case one lot did not pass and parts from another lot that did pass were used in the Cassini hardware.

Section 3.0 Approach

The objective of the electromigration review program was to check each lot of each electromigration susceptible device types and usage for meeting the part mission success probability criteria with the least expenditure of resources. To achieve this the following procedure was used.

A part minimum lifetime and probability of successfully completing the mission was established. As each electromigration sensitive part flowed through the failure analysis laboratory for DPA, the appropriate cross-section of the metallization was measured for the electromigration calculation. Depending on the internal structure, metallization cross-sections, and function of the device, the cross-section used in the calculation was either the Vdd bus, the Vss bus, a signal line, or an output line. The analyst in the Part Failure Analysis Laboratory then used the manufacturer's specified maximum allowed current for these lines to calculate current densities. The current was assumed to be a continuous d.c. current for calculation purposes. This is conservative since most devices in usage do not operate with a continuous d.c. current. The current density calculation was normally included in the DPA report.

A program developed by Dr. E. Scheuer and Dr. K. Wanchoo to calculate part electromigration survival probability for the Galileo mission was modified to calculate the probability of a part surviving the Cassini mission. The passing criteria established by the Electronic Parts Engineering Office was that the median time to failure (MTTF) of a part must be equal to or greater than three mission life times. This is equivalent to a probability of survival (P_s) for the mission of 0.99999. The P_s value was also used in the calculations because there might be a need to combine part probabilities to see if a subsystem reliability would or would not be met.

If a device did not pass the criteria using allowed currents and temperatures, the next step was to contact the appropriate subsystem reliability engineers (SRE) to obtain the actual currents that will flow through the area of concern and obtain the calculated part junction temperatures in place of the initially assumed maximum junction temperature for all electromigration sensitive parts. If a part type and application still did not pass, additional information (i.e. RMS currents) reflecting more details of the application conditions would be obtained and used in the P_s prediction. If a part still failed, the subsystem P_s would be calculated taking into account all subsystem redundancy. The minimum acceptable P_s of a subsystem for the Cassini mission for electromigration was set at 0.999. If the subsystem criteria would still not be met by the user subsystem the circuit designer would be asked to change the parts usage or redesign to meet the criteria. Those who do not want to make a change would have to submit a waiver for project approval.

Section 4.0

Analysis Details

The electromigration probability of survival of a device was calculated using Black's Equation for the MTTF, with a log normal distribution assumed in the calculation of the probability.

Black's Equation is $t_{50} = B_{50}A/J^n(e^{E_a/kT})$

t_{50} = MTTF

A = cross-section area of the line in question

J = current density in Amps/cm² = I/A

I = current through the cross-section area

n = exponent of J. n = 2 is normally assumed and is also assumed here.

E_a = activation energy. E_a = 0.558 eV is used (obtained from a 1982 paper by Black).

k = Boltzman's constant = 8.62 X 10⁻⁵ eV/°K

T = Absolute temperature of the metallization involved (assumed the same as the junction temperature). Initial temperature assumed is 70°C.

B₅₀ = a constant (from the same paper).

In calculating the probability of successfully completing the mission, a mission length t = 105,000 hr was used for engineering subsystems and 54,000 hr for science instruments. A standard deviation (sigma σ = 0.40) was used in all cases. This sigma also came from the 1982 paper by Black. Ideally experiments would be performed for each manufacturing line to determine E_a, B₅₀, and sigma for the process. These could then be used in the MTTF and probability calculation for each part type and lot evaluated. However, this would be a very expensive process. Instead E_a, B₅₀, and

sigma from the aforementioned paper was used. The values of E_a , B_{50} , and sigma used are neither optimistic nor conservative, but represent typical values one might expect to obtain when electromigration experiments are conducted.

The 70°C junction temperature used in each calculation is the maximum temperature a derated microcircuit or transistor is allowed assuming a maximum electronic bay temperature of 35°C. Under normal conditions bay temperatures will run between 25°C and 35°C. Included in the mission time is the estimated pre-launch ground time as well as the actual mission time. In addition to the 105,000 hr, the equivalent time at 70°C of a static burn-in of 192 hr at 125°C and a dynamic burn-in of 240 hr at 130°C was added.

Most, but not all parts passed the initial MTTF and P_s calculation using the manufacturer's maximum allowed dc current and a metal temperature of 70°C. More accurate currents and metal temperatures were obtained from the SRE's for particular applications that did not pass the first MTTF and P_s gates. Except for one lot that was not used, all applications for all device types and lots reviewed passed the established reliability criteria using the more accurate currents and temperatures.

During the review process the status of the analyses was tracked in a data base. The Cassini data base includes all devices that had been received for DPA and shows which parts passed or failed the three mission lifetimes and 0.99999 criteria at any given time. A separate part/subsystem detail report was published biweekly and distributed to the SRE's, parts DPA analysts, and project assurance management providing the status of the parts being evaluated. This report also included any information required from the SRE's to make particular MTTF and P_s calculations.

Section 5.0 Results

A total of 158 analyses were performed with 21 devices requiring more detailed information and analysis by an SRE.

There were some cases where a DPA cross-section was not obtained for a later lot. In such cases the earlier measured cross-section dimensions used in the electromigration equation were reduced by 10 percent, and the calculation made with the reduced cross-section. A 10 percent cross-section reduction from one lot to another is considered a conservative estimate by our part specialists for the part types involved. In some cases the part specialists provided worst case currents.

All the electromigration susceptible devices in a widely used hybrid, the Solid State Power Supply (SSPS), were analyzed for electromigration life by JPL, and passed.

Honeywell Gate Arrays were examined using the standard JPL E_a , B_{50} , and sigma in the reliability calculations. In addition, values of E_a , B_{50} , and sigma from Honeywell's process data were used in the electromigration calculations. The Honeywell parts passed both analyses.

One lot of a Harris 6617 PROM (T/N 2L016) that had thin metal and did not pass the electromigration criteria. That lot was not used, and the parts are to be tagged as not meeting the electromigration life criteria for Cassini. The parts used on Cassini come from other lots that passed.

There were a few devices in which the metallization was not pure aluminum. For these few devices small amounts of copper were added to the aluminum to prolong electromigration life, and in others a different combination of metals was used for the

same reason. The parameters used in the calculations for these devices was the same as for pure aluminum. They all passed.

Section 6.0

Stress Voids/ Electromigration and Concern

Stress voids in aluminum metallization are the result of mechanical forces on the metallization that are sufficient to transport mass of some of the aluminum. The forces come from the manufacturing process as a result of differences in thermal expansion of the aluminum and the passivation layer placed on top of the aluminum. After the passivation layer is put on the aluminum both are cooled and the differences in thermal coefficients of the materials leaves a residual stress on the aluminum. If the residual stress is strong enough voids in the aluminum can occur to relieve the stress.

Stress voids can affect electromigration because the current density in the aluminum at the area containing the voids is increased, and thereby can cause a decrease in the electromigration life of such parts.

Mil-Std-883 allows a decrease in the metal cross-section of microcircuits up to a maximum of 50%. Any reduction greater than 50% is a cause to reject the lot. Each lot of each microcircuit type purchased normally has one to three parts from the lot DPA'd. Part of the DPA is to examine the metallization within the device against the 50% criteria. One lot of devices, Harris HCS160, lot number 946618D, was rejected for stress voids. It was also noted that the DPA'd part from one lot of Harris HCS245 devices had voids with a maximum void of 15%. (Although not required, being aware of the possible electromigration effects, it is likely that voids or thinning below 50% would

be noted by DPA specialists). This led to additional work by Harris and JPL. Harris performed temperature cycling tests (up to 300 cycles; -65°C to 150°C), unbiased bake for 1000 hr at 125°C, 180°C and 225°C, and biased life test at 125°C for 1000 hr on samples from a HCS245 lot initially with voids, samples from a lot of HCTS109 devices initially without voids, and samples from a lot of HCS160 devices initially without voids. The maximum size void and number of voids in the devices tested were observed and reported in a test report. In all cases observed voids were < 20% of line width. The number of voids observed at different stages of the tests some times decreased and some times increased. There was no trend of either increasing sizes of voids or increasing the number of voids. Harris concluded that there would be no reliability risk using the parts with voids tested. As a result of the void concern part failure analysts rechecked the previously DPA'd parts from Harris for voids and found none. A 20% cross-section reduction was used in the electromigration probability calculations for this HCS245 lot. The lot passed the electromigration criteria.

There were still some concerns at JPL because: 1) the accelerated life tests performed by Harris were not long enough to simulate the Cassini life of the parts at operating temperatures, 2) different sets of parts were analyzed at different stages of testing, and 3) the parts tested were not exposed to combinations of environments that simulate the Cassini mission. A test plan was generated to achieve this and a parts engineering review was held to determine if the test should be proposed to the Cassini Project. The conclusion reached was that it would not be proposed because it was considered a low risk. See attachment 1.

Section 7.0 Summary

The electromigration evaluation program was established to provide a systematic, orderly evaluation of the electromigration susceptibility of Cassini microcircuits and transistors. This was accomplished by establishing an acceptability criteria and evaluating sample devices from each lot received against the established criteria. The program was managed by Office 507. A report was developed showing status of each part being analyzed. The report included the responsible SRE for each particular device that needed additional analysis. These reports were periodically provided to the SREs, Part Failure Analysis Group, Electronic Parts Management, and Cassini Project Product Assurance Management. Information needed to complete the evaluation of particular devices was mainly provided through direct communication with the individuals involved. All microcircuits and transistors to be used in Cassini hardware have passed the established MTTF and P_s criteria. There was no need for design changes or waivers.

Section 8.0 Recommendations

The electromigration analysis of the Cassini parts showed no concerns for the Cassini mission life. This study and other research brought out some questions that should be addressed for future missions. These items are presented below.

The acceptance of a 50% reduction in metallization, due to metal notching, voids, etc. per Mil-Std-883, can lead to a substantial mission electromigration risk, depending upon the length of the mission and the values of the other parameters of the equations used to predict electromigration life. If we accept the cross-sections used in our Cassini calculations as 50%, we would likely find a number of devices that would not pass the established acceptable mission risk criteria of 0.99999 for P_s . The question of what should be an allowable metallization width reduction, taking into account electromigration needs to be addressed by the applicable device manufacturers and users.

All electromigration sensitive devices that are DPA'd at JPL should be examined for metal cross-section reduction and any reduction observed reported in the DPA report. The report should identify the metal line (Vdd, Vss, Output, Input, Signal Line) with the reduction. This information can then be used in assessing the reliability risk of the devices involved.

Using the Mil-M-38510 current density limitation of 5×10^5 Amps/cm² cross-section by itself, as a mission criteria for electromigration acceptability, can lead to higher electromigration risks than are acceptable for particular projects. This is only one factor in the electromigration equations. Other factors are the activation energy, corresponding B term, temperature, length of mission, and sigma of the failure distribution. There is a need for a more comprehensive criteria taking these other factors into account. An electromigration specification should include requiring electromigration sensitive device manufacturers to periodically establish activation energies, corresponding B terms and sigma's for parts made using their particular

processes. NASA with the help of the semiconductor industry should develop uniform procedures for determining these parameters. Actual values for these terms could then be used in electromigration life predictions.

Manufacturer's tests for electromigration involve accelerated testing of metal strips. The lab should look into the possibility of running electromigration accelerated life tests on actual parts and comparing the results with the strip test predictions. This would validate or invalidate the strip predictions.

There have been some reports of resistance changes in metallization prior to some lines opening due to electromigration. This occurrence has been acknowledged by users of such devices in the field and that timing is altered due to the RC changes associated with such lines. Further investigation is needed to establish criteria for allowable RC changes especially with barrier metals and the impact on device performance and mission reliability.

There is a need for more work in the area of the combination of stress voids and electromigration. Currently it is not known if an inspection for stress voids in a DPA showing no voids will later turn up some voids. It is also not known if a given observed set of voids would get worse over time due to further stress relief alone. Although there has been some work performed that shows negative effects in MTTF, there is a need to comprehensively address this issue and develop some experiments using temperature cycling and x-ray diffraction methods to better assess electromigration life combined with voids or the potential for voids.

Attachment 1
follows

To: Larry Wright
From: Shri Agarwal *SA*/Mike Sandor *MS*
Subject: Conclusions from Harris Metal Stress Voids
Concerns Meeting July 21, 1995

This memo summarizes the conclusions from the July 21, 1995 meeting. Present at this meeting was L. Wright, R. Kemski, E. Svendsen, S. Agarwal, and M. Sandor.

The purpose of this meeting was to report on all our findings (Harris/JPL) regarding the concerns and issues of using parts on Cassini with cold metal processing. The original concern stemmed from JPL DPA results that showed evidence of metal stress voids on lots received from Harris that had cold metal processing. One lot was rejected for exceeding 50% voiding.

A test plan was proposed to quantify the unknown risks and the long term reliability associated with using such parts having evidence of metal stress voids. To implement this plan required ~ \$15K from the project and approximately 12 weeks to complete.

Conclusions from this meeting:

The risks associated with using Harris HCS138, HCS164, and HCS245 lots with stress voids was believed to be low based on the limited physical evidence available and the parts usage. It was further decided by the Section that the proposed test plan to quantify the risk was not warranted nor prudent because of limited funding.

Concurrence:

L.W. Wright
Mgr. Office of Electronic Parts Engineering

Distribution:

R. Kemski E. Svendsen D.Scott

METAL STRESS VOIDS
July 21, 1995 REVIEW
for CASSINI

1. Original Cause for Concern

Stress voids seen on cold metal products from Harris (JPL DPAs)

- HCS160 lot #94618D was rejected for stress voids (>50%; was replaced-ok)
- Currently using lots with stress voids which met 50% criteria (i.e. $\geq 50\%$ of metal remains)
HCS138(1 lot; kitted:244), HCS164(1 lot; kitted:185), HCS245(6 lots; kitted:551)

2. Work Done

a. HARRIS

Harris evaluation report of metal voids on random lots (Report dated 11-10-94)

- Temperature cycling -65°C to +150°C for 100, 200, and 300 cycles
- Unbiased bake for 1000 hrs at 125°C, 180°C, and 225°C
- Biased life test at 125°C for 1000 hrs

b. JPL

- Literature search on Stress Voids
- Review of Lynn Lowry's stress void data
- Performed X-Ray diffraction on parts exhibiting stress voids
- Contacted manufacturers/vendors to verify evidence of failures due to stress voids
- Ran sensitivity plots on Harris parts to determine probability of EM survival vs stress voiding

3. Conclusions from Work

a. HARRIS

- **Results from Temperature Cycling are:**
 1. **Voids remained less than 20% of line width**
 2. **Mean void count went down with increased cycles**
- **Results from unbiased bake showed no significant effect on stress voids**
- **Results from life test showed no significant effects on stress voids**

Harris Conclusion: No reliability risk due to metal voids

b. JPL

JPL conclusions based upon review of Harris work/data:

- **Temperature cycle SEM micrographs show that typical stress voids are larger after temperature cycling**
- **Some evidence of increased size of voids after 1000 hr life test**
- **No data to look at the combined effect of temperature cycling and life test that simulates the Cassini mission**

JPL conclusions based upon JPL work/data:

- **Based upon Lynn Lowry's work, metal stress is relieved as the no. of temp cycles increases**
- **We confirmed that metal stress is relieved as a result of life test and/ or temperature cycling**
- **IBM/DEC claim (unofficial) field failures caused by metal stress voids**
- **There is an industry wide concern on metal stress voids**
- **It has been demonstrated that the mean time to failure (MTF) for single layer line widths decreases with increasing void severity (Ref:AT&T Bell Labs)**

- Sensitivity plots show the HCS245 (with cold metal) would fail Cassini EM probability criteria if stress voids exceed 85% of line width using $E_a = .558$ (54HCS138 fails EM with 70% voiding)

4. What is the Residual Concern & How Large is it ?

- Stress voids that degrade the performance of parts is possible and a moderate risk on parts having stress voids
- Hard failures due to electromigration without voids is unlikely to happen and it is a low risk
- Hard failures due to electromigration with voids is a low to moderate risk
- Long term reliability aspects of stress voids are unknown, and it is an unknown risk

5. Proposed Test Plan

See IOM 507-D-113-95, dated 5-4-95 with modification that we now propose to run two groups of parts side by side, one with $T_j = 135^\circ\text{C}$ and the other with $T_j = 160^\circ\text{C}$. The group with $T_j = 160^\circ\text{C}$ has been added to accelerate the data gathering (from 31 wks to 12 wks).

6. Possible Outcomes and Actions

1. Nothing happens (impact of any stress voiding is negligible) \Rightarrow No further action needed
2. Parts degrade (verified by electrical testing and SEM inspection and attributed to stress voiding) \Rightarrow Alert the users and review all part applications
3. Parts fail due to significant stress voiding and ensued electromigration \Rightarrow Alert the users and review part applications. Replace all or some of cold metal parts

7. Decision Whether to Request Cassini for \$15K to conduct the proposed test

Yes •

No •

Notes:

- a. A possible consequence of this test is that all or some of the parts might have to be replaced (cost impact estimated to be \$100K to \$500K)**
- b. At this time we recommend no procurement action be taken, until such time as the test results indicate there is a problem and we conclude there is a significant risk to fly parts with stress voids.**

Attachment 2

follows

| | | | | | | | | | | | | | | | | |
|-----------------|---|----|------------------|-------------|-------|------|-------------|----------|----------|-------|--------|----------|------------|-----------|------------|--|
| 0 | 1 | 9 | RH108AW PASS | 1.41904E+15 | 0.558 | 0.40 | 6.39E-07 | 1.25E+04 | 7.99E-03 | 2,602 | 3,980 | -22.52 | 1.00000000 | 2 | 1.00000000 | |
| 0 | | | | 1.15000E+18 | 0.302 | 0.60 | 6.39E-07 | 1.25E+04 | 7.99E-03 | 787 | 1,097 | -11.82 | 1.00000000 | 2 | 1.00000000 | |
| 0 | | | | SRE: | | | FA/T#: 5492 | | MFG:LNT | | TTFyr= | | | 103839.13 | | |
| 0 | | | | SPECIALIST: | | | SUB S: | | TTFyr= | | | 14630.66 | | | | |
| STATUS:APPROVED | | | | | | | | | | | | | | | | |
| 0 | 1 | 10 | RH119AH PASS | 1.41904E+15 | 0.558 | 0.40 | 8.94E-07 | 1.34E+05 | 1.20E-01 | 2,602 | 3,980 | -11.49 | 1.00000000 | 2 | 1.00000000 | |
| 0 | | | | 1.15000E+18 | 0.302 | 0.60 | 8.94E-07 | 1.34E+05 | 1.20E-01 | 787 | 1,097 | -4.47 | 0.99999605 | 2 | 0.99999210 | |
| 0 | | | | SRE: | | | FA/T#: 5494 | | MFG:LNT | | TTFyr= | | | 1264.18 | | |
| 0 | | | | SPECIALIST: | | | SUB S: | | TTFyr= | | | 178.12 | | | | |
| STATUS:APPROVED | | | | | | | | | | | | | | | | |
| 0 | 1 | 11 | RH137KPR PASS | 1.41904E+15 | 0.558 | 0.40 | 1.50E-05 | 2.13E+05 | 3.20E+00 | 2,602 | 3,980 | -16.23 | 1.00000000 | 2 | 1.00000000 | |
| 0 | | | | 1.15000E+18 | 0.302 | 0.60 | 1.50E-05 | 2.13E+05 | 3.20E+00 | 787 | 1,097 | -7.62 | 0.99999999 | 2 | 0.99999998 | |
| 0 | | | | SRE: | | | FA/T#: 5570 | | MFG:LNT | | TTFyr= | | | 8394.84 | | |
| 0 | | | | | | | | | | | | | | | | |

Attachment 3

follows

**INFORMATION IS
COMPLETE**

| SRE | Part # | Subsys | Assy | List | Rated Max I (mA) | Actual Max I (mA) | Tj (c) | On Time (hrs) | Comment |
|---|----------|--------|------|------|---------------------|----------------------|-----------|------------------|--------------------|
| C.Faulkner | 54HCS373 | MAG | DPU | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| C.Faulkner | | CDA-1 | HRD | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| | | CCCB | OPTS | 2 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Not allocated part |
| C.Faulkner | | MAG-2 | FGM | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| | | GCMS | GCMS | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| J. Harrell | | RFS | TCU | BIU | 2.00E-01 | 2.40E-02 | 70 | 105000 | Engineering(Pass) |
| | | INMS | 1 | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| | | CIRS | IDS | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| T.Pham | | ISS | ME | CCE2 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| S. Duran/D.Hykes | | AACS | EGE | OO1 | 2.00E-01 | 2.40E-02 | 70 | 105000 | Engineering(Pass) |
| C.Faulkner | | RPWS | UOI | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| C.Faulkner | | RPWS | IRFU | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| C.Faulkner | | CDA-2 | ME | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| C.Faulkner | | CAPS | OO1 | OO1 | 2.00E-01 | 2.40E-02 | 70 | 44000 | Science(Pass) |
| This part passes electromigration for science and engineering based on I _{max} actual current = 24ma. | | | | | | | | | |

END OF REPORT